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THE BUILDING OF THE COLORADO ROCKIES

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PART I

INTRODUCTION

Many phases of geology involve little more than an understanding of what has taken place at or near the surface of the earth. They can thus be studied more or less directly. A study of diastrophism, however, involves in addition a consideration of what has taken place at greater depths. The visible mountain range is but the outward expression of more deeply operating forces.

Its surficial features may be fairly well appreciated; but its deeper portions are as yet very imperfectly understood. Furthermore the visible expression is material, while the formative process is dynamic. The deeper and dynamic qualities are thus to be unraveled only indirectly by special methods.

In Chamberlin and Salisbury's *Geology*[1] a method has been given for deducing the thickness of the earth shell involved in a given case of folding. This method utilizes the principle that if the amount of crustal shortening be known and also the amount of uplift resulting from the folding, the depth of the deformed block may readily be calculated. It is first tentatively assumed that the folding process has occasioned a change of shape, but has only produced a negligible change of volume, the cubic contents of the deformed block being essentially the same after folding as before. If this assumption be allowed, the product of the original length of the section before folding times the amount of uplift resulting from the folding, will equal the amount of crustal shortening times the depth of the folded zone. Since the indications are that the increase in density and reduction in volume of the deformed mass in cases of ordinary open folding are relatively slight and can if necessary be covered by a corrective factor, this method appears to be trustworthy.

An application of these principles by a trial of this method upon the Appalachian Mountain system led to some very unexpected results.[2] The mountainous belt of central Pennsylvania having been selected for the trial, because folding is so typically displayed there, a strip across the mountains from Tyrone to Harrisburg was measured and its cross-section plotted to scale. The plotted section was then divided into six subdivisions. Applying the method above outlined, the depth of the folded zone was calculated separately for each subsection. The result was the discovery that the two shallowest sections were on the two margins of the folded region, while the deepest portion was in the middle of the range. This would indicate that the shape of the deformed

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[1] II (1906), 125–26.

[2] Rollin T. Chamberlin. "The Appalachian Folds of Central Pennsylvania," *Jour. Geol.*, XVIII (1910), 228–51.

Appalachian mass in central Pennsylvania was that of a triangular prism, or wedge, which apexed downward in the middle of the range. Though the wedge-shaped mass was a result quite unexpected, it did harmonize well with various theoretical considerations. In fact it not only appeared reasonable of itself, but seemed to suggest that the principles developed might well be of very general application to mountain building, and might also find some application to plateaus and continental sectors. The wedge-shaped block and wedge dynamics in deformation seemed to open up possibilities along a new line. In view of this, it seemed desirable to apply this method of inquiry to some other mountain systems. For this work the Rocky Mountains were the most available, and as a result of preliminary scouting in the summer of 1913 the section in the vicinity of the Denver and Salt Lake Railroad (Moffat Road) in northern Colorado was selected for the trial. The strip from the Great Plains near Lyons to the Grand Hogback at Glenwood Springs affords perhaps the most characteristic section which can be selected, and is at the same time readily accessible. The special field work for this cross-section was done largely in the summers of 1915 and 1916, besides which short supplementary visits were made in 1917 and 1918, including many trips to points off the section for collateral suggestions.

THE COLORADO ROCKIES

The Rocky Mountain system extends from the Endicott Range of northern Alaska southward as far as central New Mexico, where it gradually fades out. It is a belt of varying width and structure. In Alberta and British Columbia the Rocky Mountain system, according to Daly, is very definitely bounded by the Great Plains on the east and the Rocky Mountain trench on the west.[1] It is bordered on its eastern margin throughout many degrees of latitude by great overthrust faults. In its western part, though faults continue to be numerous, folding becomes more prominent.[2] Characterized thus structurally, the Rocky system continues southward nearly halfway across the state of Montana.[1] The regular, linear, faulted chain here loses its distinctiveness and identity, and gives way to an irregular group of scattered mountain clusters in west central and southwestern Montana. Many of these have resulted from igneous outbursts, and exhibit the results of vertically acting forces fully as much as horizontal thrusting. Progressing southward across Wyoming, the ranges of the Rocky group tend to come together more closely in alignment and form a more distinct, continuous chain. But the characteristic structure of the system has changed. Gentle, open folding has replaced thrust faulting as the key structure. This continues across Colorado and into New Mexico.

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[1] R. A. Daly, "Geology of the North American Cordillera at the Forty-ninth Parallel," *Geol. Surv. Can., Memoir 38* (1912), Pl. III and p. 27.

[2] R. G. McConnell, "Report on the Geological Features of a Portion of the Rocky Mountains," *Geol. Surv., Can.*, II (1886), Part D, pp. 31 to 40.

On many maps the western half of the state of Colorado gives the impression of a tangle of mountains which manifest but little order in arrangement. Such, however, is not the case. The Rocky Mountains enter Colorado from the north as two distinct ranges—the Front Range on the east and the Park Range to the west. Southward these two ranges gradually converge. Though the Park Range dies out in the vicinity of Buena Vista, it is replaced, *en échelon*, by the Sawatch Range. Farther south, in the neighborhood of Salida, the Sawatch chain breaks down and is replaced in turn by the Sangre de Cristo Range. In about the same latitude the Front Range dies down and is replaced south of the Arkansas River by the Wet Mountains. The convergence continues until the two groups of ranges come together near La Veta Pass, from which point southward into New Mexico the entire Rocky Mountain system comprises but a single serrate ridge—the Culebra Range, or southern Sangre de Cristo Mountains. The pattern on the map is represented somewhat approximately by the letter Y, though the two upper branches do not converge quite so rapidly as in the printed letter, and the *en échelon* arrangement of the individual ranges disturbs, to a certain extent, the smoothness of alignment (Fig. 1).

This Y includes all of the Rocky Mountain system proper, which is essentially a folded system in Colorado. West of the

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[1] Bailey Willis, "Stratigraphy and Structure, Lewis and Livingston Ranges, Montana," *Bull. Geol. Soc. of Amer.*, XIII (1902), 305–52; F. H. H. Calhoun, *U.S. Geol. Survey, Prof. Paper 50* (1906), pp. 9–10.

Rockies proper are several scattered mountain groups, such as the San Juan Mountains, Elk Mountains, West Elk Mountains, and Flattop Mountains, which mark spots of excessive Tertiary vulcanism. Structurally they are quite distinct from the folded Rockies proper, and occur as isolated groups in the midst of comparatively undisturbed, flat-lying sedimentary rocks. There are also some local domelike upwarps in the western part of the state. These local upwarps and the isolated groups genetically related to Tertiary vulcanism should be sharply differentiated from the Rocky Mountains proper—the folded range. The history of the impressive San Juan group has been worked out in detail by Cross,[1] Atwood,[2] and others.

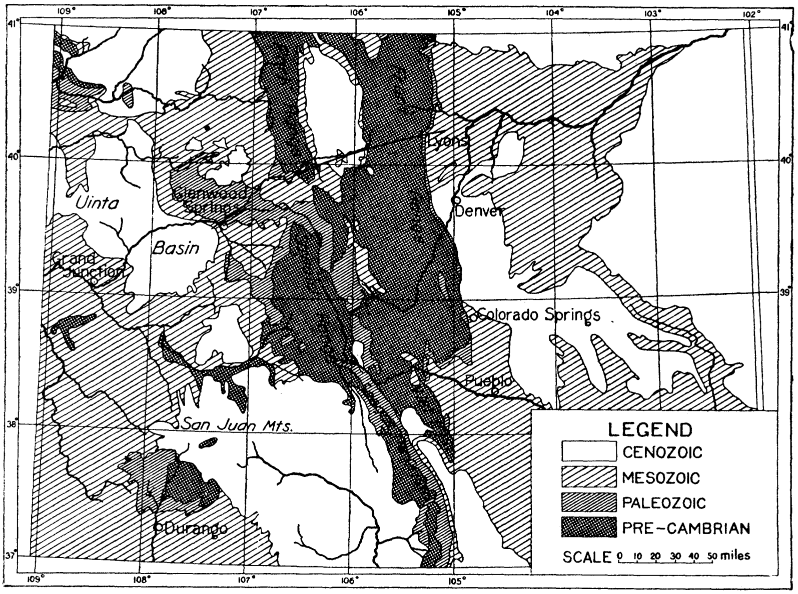

FIG. 1.—Geologic map of Colorado (after R. D. George). The darkly shaded pre-Cambrian areas delineate rather closely the pattern of the Rocky Mountains within Colorado. The ranges converge southward in *en échelon* arrangement roughly suggesting the letter Y.

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[1] Whitman Cross, *U.S. Geol. Survey, Geol. Atlas,* Needle Mountains, Rico, Silverton, Telluride, and other folios.

[2] W. W. Atwood, "Eocene Glacial Deposits in Southwestern Colorado," *U.S. Geol. Survey, Prof. Paper 95-B* (1915), pp. 22–24.

The differentiation of Colorado's mountains into the Rocky System proper and the subordinate scattered groups mostly associated with Tertiary vulcanism is apparent on either the topographic or the geologic map of the state.[1] The Rocky Mountain Y has a pre-Cambrian granite backbone throughout nearly the whole of its extent. In fact, the pre-Cambrian areas of Colorado, except for a large area of igneous and metamorphic rocks south of the Gunnison River, delineate very well the pattern of the Rocky Mountains. The southward converging of these folded ranges of old rocks, which taper into a single mountain ridge, appeared significant and possibly suggestive of the type of deformation which has taken place. It seemed to imply some sort of wedge dynamics below.

HISTORY OF THE MAIN RANGE

The present Rockies are not the first mountain system developed within the area of Colorado. After a flooding of the region by early Pennsylvanian seas there arose, before the close of the Pennsylvanian period, an ancestral Rocky Mountain range.[2] The elevation of these ancient Rockies has been assigned by Lee "to the period of diastrophism usually called the Appalachian Revolution which wrought world-wide changes in climate, geography, and biology."[3] But Lee recognizes that these ancient Rockies were probably uplifted before the Permian, because sediments derived from the erosion of this ancestral range have formed the Permian beds of the neighborhood. Still further, if the present tendency to place the Fountain sandstone and its equivalents within the Pennsylvanian[4] be correct, this growth of early Rockies must have taken place during the Pennsylvanian, as that period is now defined, since the sediments which made the Fountain sandstone came from the destruction of the newly uplifted range. More exact determination of the age of this diastrophism must await closer correlation of these lower Red Beds. But one may well wonder whether this ancestral Rocky Mountain building, which seems to correspond in time with a prominent period of folding in the Arbuckle Mountains of Oklahoma, may not prove to have been closely related to the mid-Pennsylvanian Hercynian orogenic disturbance recognized by Baker and Bowman in the Trans-Pecos region of Texas.[1] On the other hand, the Appalachian diastrophism would seem to have come after a portion at least of the Permian, if the Dunkard beds included in the Appalachian folded series are correctly referred, as is commonly done, to the Permian.

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[1] The Topographic Map of Colorado. R. D. George, 1913.

[2] Willis T. Lee, "Early Mesozoic Physiography of the Southern Rocky Mountains," *Smithsonian Misc. Coll.*, LXIX, No. 4 (1918), pp. 5-7.

[3] *Ibid.*, p. 6.

[4] R. M. Butters, "Permian or 'Permo-Carboniferous' of the Eastern Foothills of the Rocky Mountains in Colorado," *Colo. Geol. Survey, Bull. 5* (1913), Part 2, pp. 65-94.

It is not sufficiently clearly recognized by geologists that the diastrophism marking the closing stages of the Paleozoic was a double diastrophism,[2] comprising an essentially world-wide Hercynian orogenic disturbance—the Westphalo-Carbonide movement between the Westphalian and the Stephanian—and a more local Appalachian disturbance, the Permo-Carbonide movement which came after a portion at least of the Permian. It was the earlier, or Westphalo-Carbonide, movement that inaugurated those profound climatic changes which are recorded in widespread evidences of vigorous glaciation within the tropics, in the astonishingly wide prevalence of Red Beds the world over, and which are reflected in turn in great changes in life, and which, in view of the dominating character of these changes and their great significance from many standpoints, may perhaps not unfittingly be chosen as the dividing line between the Paleozoic and the Mesozoic.

Lee states that in few places in the Rocky Mountains can a line of separation be drawn between the Permian and Triassic rocks, while there is a much greater break in sedimentation between the Pennsylvanian limestone and the Permian Red Beds.[3] During the later Pennsylvanian and Permian periods detritus from the newly uplifted mountains was deposited nearby and formed the now prominent non-marine Red Beds. Erosion of the mountains continued through the Triassic and part of the Jurassic, approaching peneplanation before the close of the Jurassic and preparing the way for a marine invasion in Upper Jurassic times.[1] The submergence did not last long, and upon the graded plain abandoned by the sea and the peneplaned area surrounding it the streams of early Comanchean time spread out the sediments of the Morrison formation.[2]

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[1] C. L. Baker and W. F. Bowman, "Geologic Exploration of the Southern Front Range of Trans-Pecos, Texas," *Univ. of Texas, Bull. No. 1753* (1917), pp. 107–12.

[2] Rollin T. Chamberlin, "Periodicity of Paleozoic Orogenic Movements," *Jour. Geol.*, XXII (1914), 334–45.

[3] Willis T. Lee, *op. cit.*, p. 7.

The Cretaceous period was a time of very extensive marine sedimentation in the Rocky Mountain region. Lee has brought out the fact that the Dakota sandstone, and probably also the overlying marine Cretaceous formations, formerly extended uninterruptedly over the areas now occupied by the Colorado Rockies.[3] These Cretaceous beds mark the last great marine invasion of the interior of North America and are represented by a thick stratigraphic column. In waning Cretaceous times the seas shoaled and withdrew, causing marine sedimentation to give way to terrestrial deposits with included coal beds.

Laramide diastrophism.—The Cretaceous period was the long quiet before the storm. At its close the growing stresses within the earth sought relief in folding movements. These were of a pulsatory nature, for at least two distinct periods of folding have been distinguished. In northern Colorado the first of these followed the deposition of the Laramie formation of the Denver Basin. But in southern Colorado no folded formation so late as this has been preserved, owing to the greater erosion there in the interval between the folding and the deposition of the basal Eocene. In that region the last formation affected by the Laramide disturbance which has escaped removal is the Vermejo formation of the Montana group.[1] The exact extent of this diastrophic movement has not yet been satisfactorily determined for the Colorado region, principally for the reason that contacts between the Cretaceous and early Eocene within the folded portion of the range are few and very unsatisfactory, owing to the great amount of erosion which has taken place there. Folded or faulted Cretaceous beds overlain by less disturbed early Eocene strata are not found at many places in Colorado. In Wyoming, however, there are numerous sections in which the Adaville formation (upper Montana and lower Laramie) shows profound folding and faulting followed by extensive erosion before the deposition of the Evanston (early Eocene) beds, which lie in strong discord across the truncated edges of the Mesozoic strata.[2]

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[1] *Ibid.*, pp. 7–12 and 24–41; also W. N. Logan, "A North American Epicontinental Sea of Jurassic Age," *Jour. Geol.*, VIII (1900), 242–73.

[2] See C. C. Mook, "A Study of the Morrison Formation," *Ann. New York Acad. Sci.*, XXVII (1916), 31–191.

[3] Willis T. Lee, "Relation of the Cretaceous Formations to the Rocky Mountains in Colorado and New Mexico," *U.S. Geol. Survey, Prof. Paper 95-C* (1915), pp. 27–58.

In Colorado the Laramide upfolding of the Rockies resulted in a rapid erosion of the newly risen mountains and the accumulation of the Dawson arkose and the Arapahoe conglomerate near Colorado Springs and Denver, and the development of the Raton formation farther south. Some idea of the extent of the upfolding may perhaps be obtained from the amount of erosion which immediately followed. Cross has estimated that post-Laramie erosion had already, in Arapahoe times, removed from portions of the folded belt west of Denver the great total of 14,000 feet of strata, since pebbles derived from various geological horizons down as far as the Trias are found in the Arapahoe beds.[3] In the same way Lee has estimated that the conglomerate at the base of the Raton formation in southern Colorado is stratigraphically more than 18,000 feet above the crystalline and metamorphic rocks that furnished most of the pebbles found in it.[4] Lee, however, recognizes that it is not known that the older sedimentary formations were conformable and once extended continuously over the now uplifted area, but states that in any case the Cretaceous sedimentary rocks are conformable throughout, and in order that pebbles of sandstone from the Dakota and the still older Red Beds could be incorporated in the conglomerate there must have been differential uplift and erosion of more than 4,000 feet. Though making this very safe and modest estimate, Lee has expressed his belief that the actual erosion was probably very much greater than 4,000 feet. An estimate upon the Dawson arkose would probably be of similar import.

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[1] Willis T. Lee and F. H. Knowlton, "Geology and Paleontology of the Raton Mesa and Other Regions in Colorado and New Mexico," *U.S. Geol. Survey, Prof. Paper 101* (1917), p. 64.

[2] A. C. Veatch and A. R. Schultz, "Geography and Geology of a Portion of Southwestern Wyoming," *U.S. Geol. Survey, Prof. Paper 56* (1907), Pl. IV; A. R. Schultz, "Geology and Geography of a Portion of Lincoln County, Wyoming," *U.S. Geol. Survey, Bull. 543* (1914), Pl. III.

[3] Whitman Cross, "Geology of the Denver Basin in Colorado," *U.S. Geol. Survey, Monograph 27* (1896), p. 207.

[4] W. T. Lee, *U.S. Geol. Survey, Prof. Paper 101* (1917), p. 59.

Above the Arapahoe in the Denver Basin is the Denver formation, whose composition is of much significance. According to Cross the material of the Denver beds, which must have come from the highlands to the west, may be classed as débris partly from the Archean, partly from sedimentary rocks, and partly from andesitic eruptive rocks.[1] The Arapahoe strata contain little or no fragmental material derived from eruptive rocks, while on the contrary the lowest 900 feet of the overlying Denver beds are composed largely of andesitic materials and contain very little granitic or sedimentary débris. Cross says: "The andesitic masses which furnished the materials for the lower part of the Denver sediments were so situated as to effectively prevent the access of all Archean and sedimentary débris to the sea of that epoch. That is to say, the Archean and sedimentary rocks in the mountainous area drained by the tributaries of the Denver sea must have been covered by andesitic lava flows so that no material other than the eruptive débris could appear in the Denver sediments, from this, the prominent source, until erosion had laid bare, here and there, small areas of granite, of gneiss, or of sandstone."

More direct evidence of these floods of andesite, the postulated source of much of the material of the Denver sediments, has been found in Middle Park, where there is a thick formation of andesitic breccias and tuffs with conglomerate and sandstone resting unconformably upon the Cretaceous, and which is comparable to the

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[1] Whitman Cross, *op. cit.*, pp. 199–206.

Denver formation in lithological character and in its fossil plants.[1] Along the Grand River, in the line of the section which was measured as the basis for this present study of the Rocky Mountain deformation, the Middle Park formation outcrops continously for a distance of $4\frac{3}{4}$ miles. Its structure, as was first noted in the very excellent description by Marvine,[2] is basin-like. On the eastern limb of the syncline the steeply inclined, westerly dipping beds of the basal portion of this formation, form the conspicuous mountain ridge through which the Grand River flows at Windy Gap, $3\frac{1}{2}$ miles northwest of Granby. Westward toward the middle of the basin the dip rapidly lessens, and for several miles is not far from horizontal, but farther west the lower beds of the volcanic series emerge again about 2 miles east of Hot Sulphur Springs.

At Windy Gap the Middle Park formation consists of a series of breccias, tuffs, conglomerates, and sandstones dominantly of andesitic derivation. In the lower portion there are several hundred feet of coarse breccia containing many cobbles and angular fragments of andesite up to six inches in diameter. Higher up in the series the material becomes finer, and rounding by water action becomes more prominent. Within the first five hundred feet of the formation no evidence of granitic materials was observed. The pre-Laramide formations at this stage supplied very little detritus to be mixed in with the andesitic derivatives. But in time the lithological character of the accumulation underwent a change as new sources of material became available. About 1,000 feet stratigraphically above the base of the formation some very striking conglomerates appear in the hills immediately west of the Windy Gap Ridge. Well-rounded cobbles of four or five inches represent the average coarseness, though bowlders of a foot or more in diameter are not difficult to find. These cobbles are of granitic rocks and various fine-grained porphyries, particularly grayish-green andesite. The only available source for the granites is the pre-Cambrian complex, while the porphyries were as obviously derived from the flows of the Middle Park formation itself. The old granites and the Tertiary effusives are in nearly equal proportions. Above this conglomerate for another thousand feet are various arkosic sandstones and coarse conglomerates whose material has been derived from both the old granites and the young andesites. Pebbles of white and purplish vitreous quartzite are conspicuous in places.

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[1] Whitman Cross, "The Post-Laramie Beds of Middle Park, Colorado," *Proc. Colo. Sci. Soc.*, IV (1891–93), 192–214.

[2] A. R. Marvine, "Report on Middle Park," *U.S. Geol. and Geog. Survey of Colorado* (Hayden), 1873, pp. 154–92.

The import of this formation is that, either accompanying a late stage of the post-Laramie folding or soon after it, there were extensive outbursts of andesite in this portion of the Colorado Rockies. These flows were either so vast or else were so located relative to the basins where sediments accumulated, that they furnished a very large part of the detritus which made up the lower portion of the Middle Park formation, as urged by Cross, while the Archean granite contributed practically nothing. But later, after these volcanics had suffered much erosion, or else there had occurred further uplifting along the granite core of the range, or both, the granite areas supplied much coarse pebble and cobble material to the sediments which were accumulating in this basin.

Early Tertiary folding.—Since deposition this Middle Park formation has suffered a period of folding which has accentuated the structural basin by causing the basal volcanics on the eastern margin of the syncline to dip westward at angles of 50°–60° and the same series on the western margin to dip eastward at angles up to 30°. The upper beds of the formation exposed in the middle of the syncline possess only very gentle undulations which cause them to depart but little from a horizontal position.

The time of the folding movement which disturbed these beds was not closely determined in this present study. In any case it was post-Middle Park and pre-Uinta, for after the folding a long period of denudation had greatly changed the region before the beds classed as Uinta were laid down. It is possible that this is to be correlated with a prominent folding period which has been recognized in the mountains of Wyoming, and which can be more closely timed. There the folding and faulting occurred between the Fowkes formation of the Lower Wasatch and the Knight formation of the Upper Wasatch, and is represented, according to Veatch, by a break which amounts to perhaps 5,000 feet of strata.[1] But the older, post-Laramie break amounts to over 20,000 feet, and Veatch has expressed the opinion that the folding following the Lower Wasatch should perhaps be regarded as of much less relative significance than this comparison of figures might indicate, because the movements of the second disturbance were along the lines of weakness produced by the first. As to correlation, Veatch is conservative, placing the 6,000 feet of strata between these two breaks in the debatable ground between the known Cretaceous and Tertiary.

Along the western margin of the Rocky Mountain belt in the Colorado section here studied, the Grand Hogback upturn involves the Wasatch beds as fully as the Cretaceous. This may be observed to the west of Glenwood Springs, both north and south of the Grand River. At Piceance Gap to the northwest both the Wasatch and Green River beds are included in the monoclinal fold according to Gale.[2] Farther west in the Uinta Basin of Utah the Wasatch has been folded with the Cretaceous.[3] Whether this flexing on the western borders of the Rocky belt is to be correlated with the Middle Park folding within the range is uncertain. Irrespective of this it is peculiar in manifesting certain characteristics of basin-like subsidence and downwarping.

R. C. Hills has described this early Tertiary folding exhibited in certain portions of the Sangre de Cristo Range as post-Bridger, because the Huerfano beds were involved.[4] To this period of folding he has also assigned the flexing of the Grand Hogback, as well as rather widespread folding on the east flank of the front range.[5] Hills is the authority for the belief that the post-Bridger folding in Colorado was nearly as widespread and equally as intense as the post-Laramie folding.[1] It followed very closely the older Laramie lines of flexure.

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[1] A. C. Veatch, *U.S. Geol. Survey, Prof. Paper 56 (1907)*, p. 75.

[2] Hoyt S. Gale, "Coal Fields of Northwestern Colorado and Northeastern Utah," *U.S. Geol. Survey, Bull. 415* (1910), Pl. XIII.

[3] C. T. Lupton, "The Blacktail Mountain Coal Field, Wasatch County, Utah," *U.S. Geol. Survey, Bull. 471* (1912), Pl. LXII.

[4] R. C. Hills, *U. S. Geol. Survey Geol. Atlas, Walsenberg Folio*, No. 68 (1900) pp. 2–3.

[5] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), 408–19.

The post-Middle Park folding was followed by a long period of erosion in the Colorado Front Range. Erosion in fact must have been steadily at work on the main anticlines of the Colorado Rockies since their arching in the Laramide diastrophism. This long continued denudation greatly reduced the country, as is known from the fact that beds regarded as Uinta in age[2] were laid down directly upon the Archean granite over wide areas in the Grand River region of Grand County. The broad valleys and basins of the region no doubt received deep fillings of detrital material, as the country was brought toward a common level by degradation of the higher areas and aggradation of the lower. The Upper Eocene beds thus deposited exhibit in places an appreciable departure from horizontality, giving rise to a slight waviness in structure, but they seem to have suffered no pronounced folding. This warping of the Upper Eocene beds suggests that in this region there was a mild expression of the mid-Tertiary diastrophism which developed more strongly near the Pacific Coast and elsewhere.

Peneplanation.—After one or more cycles of erosion of whose details little is known, the granite ranges became an imperfect plain, above which unreduced areas remained as scattered monadnocks from 500 to 2,500 feet in height.[3] This peneplain, if such an imperfectly reduced area may be designated by that term, must have extended throughout the region of the Colorado Front Range, for remnants of it are still preserved at many points in different parts of the range. In the neighborhood of the Lyons-Grand River section, whose study constitutes the basis for the investigation in hand, these flats form conspicuous portions of the continental divide in Flattop Mountain and some of its immediate neighbors in Rocky Mountain National Park (Fig. 2). The name Flattop is correctly descriptive of an extensive flattish portion of the divide in a region of steep-sided peaks and precipitous cirque walls. The bench mark on this summit flat records an elevation of 12,364 feet. Views from the nearby peaks give the observer an excellent idea of this old peneplain. South of the Lyons-Grand River section more of the peneplain is still preserved on the continental divide. The crest of the range from the neighborhood of Arapahoe Peak to James Peak, when viewed from the Windy Gap Ridge west of Granby, presents an almost horizontal skyline whose elevation is shown by the map of the Central City quadrangle to be very close to 12,000 feet. Continuing the vision to the south of the monadnock group comprising James Peak, Mt. Eva, and Mt. Flora, the eye is again impressed by the level sky line which extends onward for many miles with little departure from the 12,000 foot elevation.

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[1] R. C. Hills, "Orographic and Structural Features of Rocky Mountain Geology," *Proc. Colo. Sci. Soc.*, III (1888–90), p. 443.

[2] Geologic Map of Colorado. R. D. George, 1913.

[3] W. M. Davis, "The Colorado Front Range," *Ann. Assoc. Am. Geog.*, I (1911), 31.

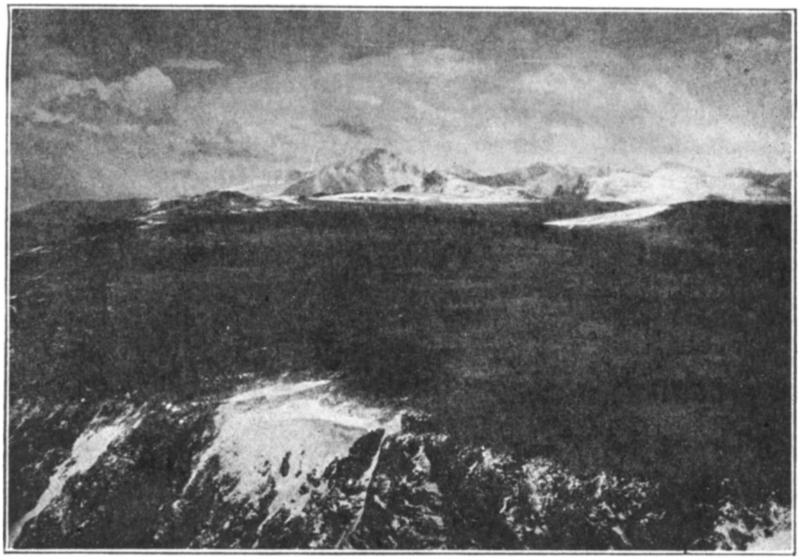

FIG. 2.—The peneplain on the continental divide. Looking southeast across Flattop Mountain (12,364 feet) to Long's Peak, a rugged peak carved from an unreduced remnant rising above the peneplain level. In the immediate foreground are the upper cirque walls of Spruce Canyon. Several other steep-walled cirques head back into Flattop but are barely visible in this view.

The age of this peneplain was not determined. No ready means of dating it was found in the time at disposal, and exhaustive search was not felt to be vital to the immediate problem in hand, though admittedly very important in the history of the range and that of the general region. Perhaps something may be learned from a comparison with more favorably situated peneplains in adjoining states. The pronounced peneplain upon the Wind River Range of Wyoming has been assigned to the middle of the Miocene by C. L. Baker.[1] Baker believes that this peneplanation was interrupted, probably later in the Miocene, by an uplift, both regional and orogenic, along the lines of the earlier Laramide movement. Westgate and Branson, however, did not feel justified in dating the peneplain more closely than mid-Tertiary.[2] Blackwelder, on the other hand, believes that the Wind River summit peneplain is of Pliocene age, for which he gives a well considered argument.[3]

In the Laramie region of southeastern Wyoming, Blackwelder has described Pole Mountain and the Medicine Bow plateau surface as remnants of a peneplain developed by the Eocene cycle of denudation, while the Sherman peneplain, at somewhat lower elevation, represents in his opinion a Pliocene date.[4] These two erosion levels, if such they be, are not far apart near the Wyoming-Colorado line, indicating that but little uplift took place between these stages; but southward in the Front Range of Colorado the relief of the country becomes steadily greater. In the Long's Peak region extensive flats are found east of the main range in the neighborhood of 8,000 feet, which is not far from the Sherman level in the Sherman quadrangle, but the summit peneplain on the continental divide is here at an altitude of approximately 12,000 feet. The Great Plains abut the foothills in the Sherman region at an elevation of about 7,000 feet, ignoring the river valleys which have cut well below this level; east of Long's Peak the plains have an elevation of only 5,000 feet above the sea. The greater elevation of the Front Range in Colorado is the result of greater upbowing of the old peneplain surface in that latitude.

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[1] Charles Laurence Baker, "Notes on the Cenozoic History of Central Wyoming," *Bull. Geol. Soc. Amer.*, XXIII (1912), 73.

[2] L. G. Westgate and E. B. Branson, "The Later Cenozoic History of the Wind River Mountains, Wyoming," *Jour. Geol.*, XXI (1913), 144–47.

[3] Eliot Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, XXIII (1915), 193–207.

[4] Eliot Blackwelder, "Cenozoic History of the Laramie Region," *Jour. Geol.*, XVII (1909), 429–44.

On the Sherman (Wyo.) sheet close to the Wyoming-Colorado line, the Sherman peneplain level is in the neighborhood of 7,700 feet above the sea. On the Livermore (Colo.) sheet next south the plain rises from about 7,000 near the sedimentary hogbacks to 8,000 feet at the west margin of the sheet. On the Mt. Olympus sheet next south the general elevation of the plain is not very different, but on the Boulder sheet adjoining Mt. Olympus on the south the plain rises from 6,500 feet elevation near the city of Boulder to approximately 9,000 feet at the west margin of the sheet near the mining camp of Ward. While there may well be some minor levels included, these elevations constitute a very evident erosion plain which slopes toward the east. The slant of the plain becomes progressively steeper as it is followed southward from Sherman, Wyoming, to Boulder, Colorado, indicating a greater upwarp of the range in the latitude of Boulder.

Davis considered this old erosion plain to have been once continuous with the so-called summit peneplain whose remnants are today seen on the continental divide at an elevation of 12,000 feet.[1] If so, it would mean that the inclination of the plain becomes greater as it nears the divide. It is natural enough that there should have been sharper tilting along the axis of the range. In the region crossed by my section, however, the evidence did not seem to be altogether conclusive. There may be two plains representing different cycles. If so, this would suggest some upwarping between and would have a bearing upon the age of the summit peneplain. But if, on the other hand, the summit plain and the lower plain to the east are truly parts of the same surface of denudation, the rather obvious recency of the latter would indicate that the summit peneplain is of late Tertiary age. The erosion plain extending from Allen's Park and Ward to the foothills near Boulder must clearly be as late as the Pliocene.

[1] W. M. Davis, *op. cit.*, p. 31 and Fig. B2, pp. 76–77.

West of the continental divide along the line of the Grand River section, remnants of a former surface of little relief are observed at various points. In Pliocene times this region, if not brought to the condition of a true peneplain, was at least greatly reduced and many extensive flattish areas developed. Preserved portions of these are seen today on the western uplands of the section at elevations for the most part between 9,000 and 10,000 feet. The Lyons-Grand River cross-section given later in this paper seems, however, to belie this statement, but that is because the drawn section closely follows the course of the Grand River and only in a few places does it rise to the upland peneplain level.

Upbowing.—Since the formation of this late Tertiary peneplain, it has been bowed upward along an axis which corresponds approximately with the present crest of the Front Range. General uplift involving some little warp also affected the region west of the Front Range and accentuated the height of several of the ranges. The movement in the Front Range was a gentle tilting in the latitude of Long's Peak, though in the foothills it may have been accompanied by normal faulting. Farther south, in the vicinity of Castle Rock and Colorado Springs, Richardson's sections of the Front Range foothills show the Dawson arkose of the early Eocene to be steeply inclined, and cut by a set of normal faults, which are there an important part of the foothill structure.[1] Finlay has placed this period of disturbance within the Pliocene Period.[2]

This uplift has given the Front Range much of its present elevation above the Great Plains to the east. Streams rejuvenated by the uplift have since carved deep canyons, which head far back in the high level plain. Leading back from the plains to the open uplands of Estes Park and Allen's Park, where roads are possible in almost any direction, are the wonderful scenic canyons of the Thompson River and St. Vrain Creek, which are young in the present cycle of erosion. On the west side of the continental divide the Grand River sweeps swiftly through the beautiful Byers, Gore, and Grand River canyons on its way westward, showing that, while the extent of the uplift varies from place to place, the Rocky Mountain belt in this latitude was bowed up throughout its full width. These are among the finest canyons in Colorado and through their high, rugged walls they testify to the extent and comparative recency of the uplift which has renewed the cutting power of the Grand River. Increased erosion on the softer sedimentary strata east of the Front Range granite area has lowered the Great Plains immediately adjacent to the foothills, thus further uncovering and sculpturing into hogbacks the more resistant beds of the steeply upturned sedimentary series of the foothill belt. The map of the Livermore Quadrangle suggests that there were

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[1] G. B. Richardson, *U.S. Geol. Survey, Geol. Atlas, Castle Rock Folio,* No. 198 (1915), pp. 10–11.

[2] George I. Finlay, *U.S. Geol. Survey, Geol. Atlas, Colorado Springs Folio,* No. 203 (1916), pp. 13–14.

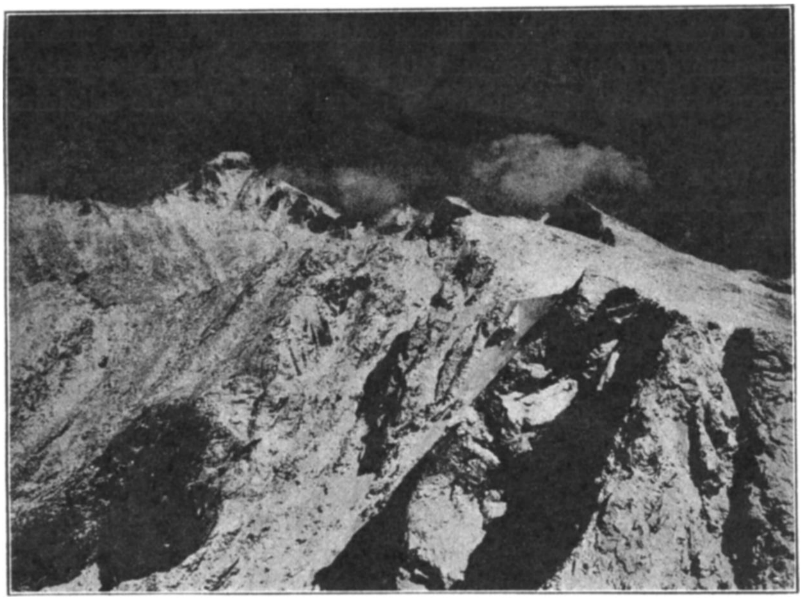

FIG. 3.—Rugged mountains sculptured from a smooth-sloped monadnock rising above the peneplain on the continental divide. Long's Peak (14,255 feet) from Taylor Peak (13,150 feet). Remnants of the smooth monadnock surface are seen on the right-hand side of the photograph in McHenry's Peak and Chief's Head. This surface was seemingly once continuous with the flat summit of Long's Peak. Glaciers stoping backward have cut profound cirques into the old surface.

at least two distinct stages in this process. Since the weaker strata of the plains reached a stage of advanced old age, two episodes of erosion have left their impress there, according to the studies of Davis.[1]

Quaternary glaciation has also greatly modified the details of the mountainous belt. By the cirquing and stoping process, serrate peaks and sharp ridges have been carved and sculptured out of the rounded monadnocks and remnants of the summit peneplain (Fig. 3). Rounded U-shaped valleys with capacious cirques testify to the potency of glacial erosion in the adjoining valleys.

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[1] W. M. Davis, *op. cit.*, p. 31. See also N. M. Fenneman, "Geology of the Boulder District, Colorado," *U.S. Geol. Survey, Bull. 265* (1905), Fig. 1 and Pl. IIIA.

[*To be continued*]